# SUPERCONDUCTIVITY - Basic

## Clapping Mode of a d-Wave Superconductor in a Magnetic Field

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We have studied a high temperature superconductor in a magnetic field. The conventional $d_{x^2-y^2}$ order parameter is admixed with $d_{xy}$ by the magnetic field. The collective modes of the system have been analyzed, and it is found that a collective mode exists in which the phase of the $d_{x^2-y^2}$ and $d_{xy}$ are opposite leading to a finite frequency as the momentum goes to zero. The in phase made goes to zero frequency for zero momentum corresponding to the Goldstone mode. Infrared absorption and NMR should be able to detect the out of phase mode, verifying the admixed order parameter.

## H-T-J Phase Diagram and Pinning Mechanism in $Ba_{1-x}K_xBiO_{3-y}$ Single Crystals

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Recent reports indicate that the Werthammer, Helfand, and Hohenberg (WHH) theory does not describe the temperature dependence of the upper critical field in the cubic superconductor, $Ba_{1-x}K_xBiO_{3-y}$ (BKBO). Fortunately, BKBO has $H_{c2}(0)$ in the range 25 to 45 T, which can still be measured using hybrid or pulsed field magnets; therefore, the *H-T-J* phase diagram and flux pinning mechanism can be studied in this material down to the lowest *T*.[1, 2]

The magnetic field dependence of the critical current $J_c$ in these superconductors is described by the collective-pinning theory.[3] Moreover, for BKBO the appearance of the so-called "peak effect" in *M(H)* isotherms is associated with the boundary between the single-vortex and the small-bundle regime of pinning. Another approach[1] drew attention to the crossover between $\delta l$- and $\delta T_c$-pinning mechanism as a reason for the peak effect.

We performed magnetization measurements of BKBO single crystals using both SQUID and cantilever beam magnetometry (CM). The high fields used allowed us to study the overall *H-T-J* phase diagram (Fig. 1). Shown in Fig. 2 is the temperature dependence of the collective-pinning length of the BKBO crystals deduced from $J_c$ versus $B$ measurements in comparison to $\xi^{2/3}(T)$ and $\xi^2(T)$-fit, which correspond to the models of $\delta T_c$- and $\delta l$-pinning, respectively. It is seen clearly that an approximation in the model of pinning by centers associated with spatial fluctuations

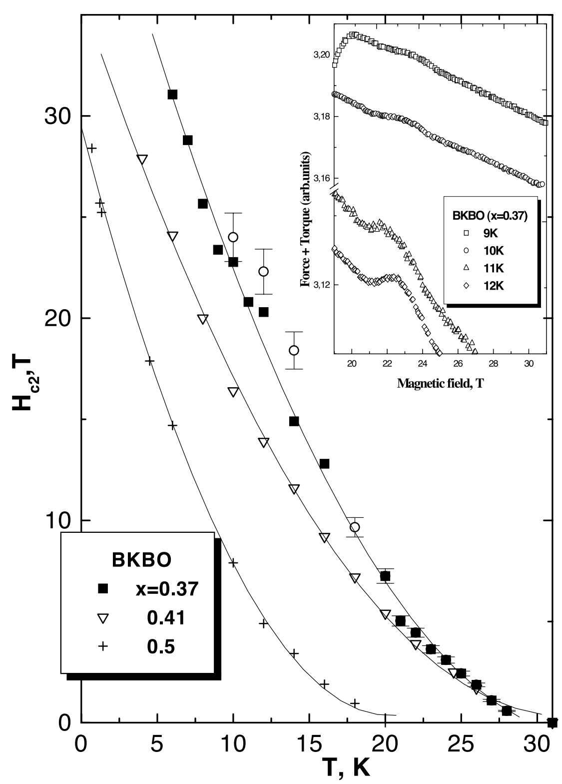


**Figure 1.** Second critical field vs. temperature of BKBO crystals recorded by CM and SQUID (empty circles – the data extracted by Gantmakher method[2]). Inset: Image $H_{c2}$ -related plateau on isotherms of force plus torque signal for the x=0.37 sample cooled at $H$~2/3 $H_{c2}$.

SUPERCONDUCTIVITY-Basic

of carriers mean free path describes adequately the $L_c(T)$ behavior. The high field results support our conclusion[1] on the unified $\delta l$- pinning mechanism, which persists in BKBO (x>0.45) over the whole temperature interval studied. The pinning centers and oxygen homogeneity suppress the peak effect in the x=0.5 sample.

- Strong upward curvature of the $H_{c2}(T)$ dependence confirms at least intermediate strength of the electron-phonon coupling in this 3D-superconductor family
- We state the BKBO (x>0.45) in the small-bundle regime flux is pinned by interaction between vortex and microstructure inhomogeneity in the crystal bulk
- On the contrary for samples with smaller x the collective pinning length is in a good agreement with a model of flux pinning by spatial fluctuations of $T_c$

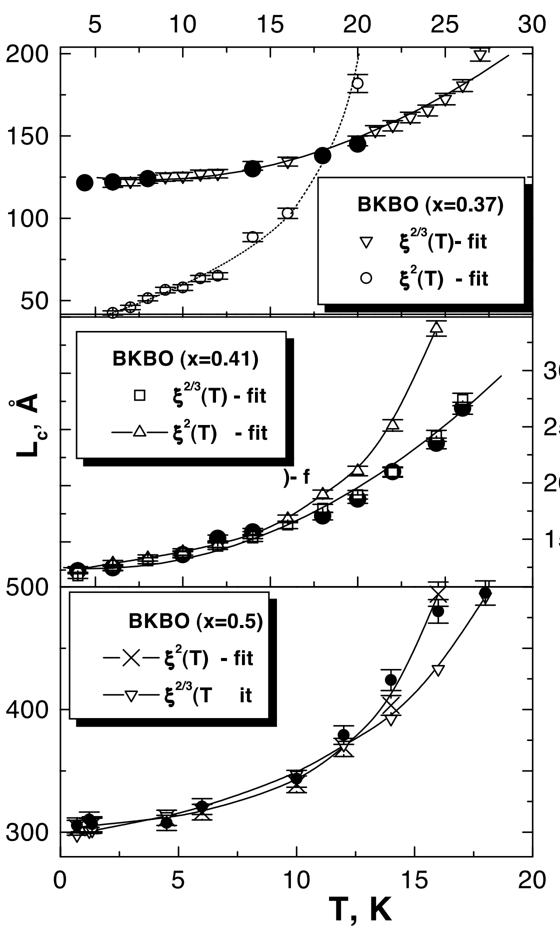


**Figure 2.** Comparison of the $L_c(T)$ data of the BKBO(x=0.37,0.41, and 0.5) extracted from magnetic measurements with $\xi^{2/3}(T)$ and $\xi^2(T)$-fit following the models of $\delta T_c$- and $\delta l$-pinning.

- Crossover between $\delta l$- and $\delta T_c$–pinning is responsible for the peak effect in this system.

**Acknowledgements:** SNB gratefully acknowledges the NHMFL's hospitality and financial support, and Dr. Bruce Brandt for help with CM measurements.

1 Barilo, S.N., *et al.*, Phys. Rev. B, **58**, 12355 (1998).
2 Barilo, S.N., *et al.,* Physica B, (to be published).
3 Blatter, G., *et al.,* Rev. Mod. Phys., **66**, 1125 (1994).

## Normal State of the Unconventional Superconductor $Sr_2RuO_4$ at Low Temperatures in High Magnetic Fields

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The layered perovskite oxide $Sr_2RuO_4$ has attracted considerable experimental and theoretical attention since the discovery of superconductivity in this compound six years ago. There are now several experimental indications for unusual spin-triplet superconducting pairing in this material, possibly mediated by incommensurate spin fluctuations. On the other hand, we are able to understand and classify the normal state of $Sr_2RuO_4$ as a conventional, though very anisotropic, Fermi liquid. The material therefore provides us with a unique opportunity to study the origin of unconventional superconductivity.

If spin fluctuations play the dominant role in the renormalization of the electronic properties and the mediation of superconducting pairing, it is instructive to probe how the situation changes as one applies a strong magnetic field. In a quantum critical point scenario of superconductivity, such as spin fluctuations near a magnetic instability, one would almost invariably expect a magnetic field to change the degree of criticality, as long as the magnetic field couples to the order parameter in question.

We therefore performed a high-field study of the de Haas-van Alphen (dHvA) effect in a high-purity sample of $Sr_2RuO_4$ ($T_c$ = 1.44 K), using a capacitive torque sensor in a 33 T resistive DC magnet. To extend previous preliminary experiments on a $^3$He system, we used a portable dilution refrigerator to reach temperatures down to 30 mK. It is only at such low temperatures that the magnetization contribution of the heaviest Fermi sheet reaches its full extent, and the quantum-oscillatory magnetization under these conditions is shown in Fig 1.

That figure also shows the dHvA frequency spectrum, with three fundamental peaks corresponding to the three Fermi surface sheets, and the envelopes, i.e. field-dependent amplitudes, of those three oscillatory components. Beat patterns are clearly visible in all three envelopes, including γ where such beats had so far remained unobserved. The reason for those beats is the corrugation of the underlying Fermi cylinders.

However, further analysis of our results shows that the normal state Fermi liquid in $Sr_2RuO_4$ is remarkably unaffected by the strong magnetic field. To within

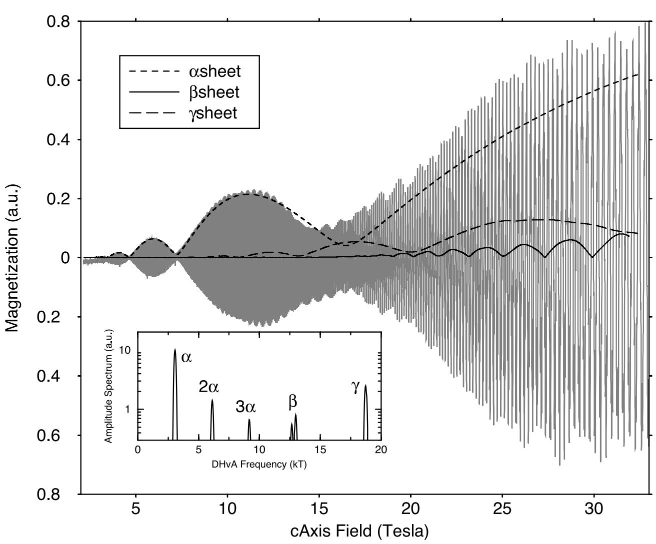


**Figure 1.** Quantum-oscillatory magnetization of $Sr_2RuO_4$ in a long field sweep from 33 T down to 2 T (thin grey line), at 30 mK with the field near the c-axis. The dHvA frequency spectrum, taken over the field range 25 T to 33 T, is given in the inset. The thick black lines show the envelopes of the oscillations corresponding to the three fundamental frequencies.

the limits of our experimental resolution and up to the highest fields employed in this study, the Fermi surface, quasiparticle renormalization, and spin susceptibility stay invariant. It remains to be explored whether this can be reconciled with a magnetic quantum critical point scenario for superconductivity in $Sr_2RuO_4$.

**Acknowledgements:** We are grateful to E.C. Palm and T.P. Murphy for their technical assistance. This work was supported in part through NSF grant DMR-NSF-9971714 and the U.K. EPSRC.

## Infrared Spectroscopy of High Temperature Superconductors in High Magnetic Fields

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The mechanism of high temperature (high $T_c$) superconductivity is one of the central unsolved problems in condensed matter physics. There are many factors that inhibit quick progress in the understanding of the high $T_c$ phenomenon. Perhaps one of the most obvious complications is that very little is known about the ground state of high $T_c$ superconductors at T~0 in the absence of superconductivity. This is because it is difficult or impossible to achieve magnetic fields exceeding the upper critical field $H_{c2}$ in most cuprates. One lesson learned from conventional superconductors is that the starting point for the understanding of superconductivity must be a clear picture of the normal ground state. The goal of this work is to fill the principal void in the studies of high $T_c$ superconductivity by performing the first infrared spectroscopy measurements in the regime where superconductivity is at least partially suppressed by high magnetic field.

C-axis spectroscopy measurements have been performed on single crystals $La_{2-x}Sr_xCuO_4$ for x=0.125 (underdoped) and 0.17 (slightly overdoped). Because the experimental setup in NHMFL allows only relative reflectivity measurements (i.e. ratios Rc[B]/Rc[0T]), absolute values of zero field reflectance Rc[0T] needed for normalization have been obtained at UCSD. Examples of raw data, obtained with the 17 T superconducting magnet at NHMFL, are shown in Fig.1. Present magnet configuration in NHMFL allows reflectance measurements with DC magnetic field applied only along the $CuO_2$ planes. This is unfortunate because the upper critical field $H_{c2}$ for this configuration is much higher then for B perpendicular to the planes. However, even in this configuration we have observed shifts in the Josephson plasma edge, indicating significant suppression of superfluid density with magnetic field (see Fig.1).

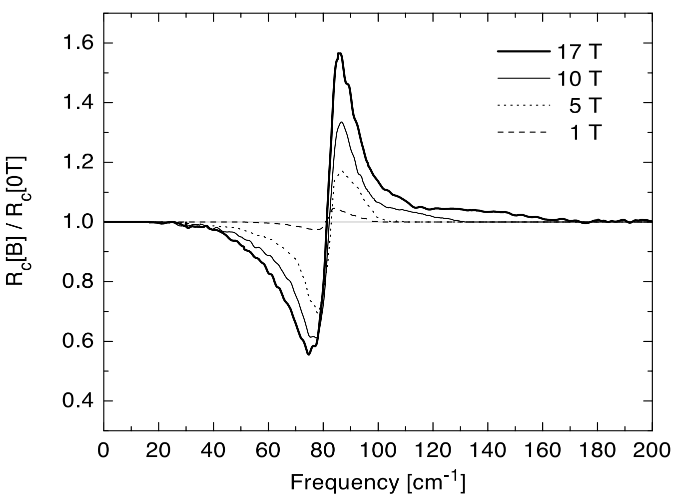


**Figure 1**. Relative reflectivity data in high magnetic fields.

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## Scaling of the AC Conductivity in Superconductors Near the Critical Temperature

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Near a second order phase transition, many physical properties become universal, in the sense that they are independent of microscopic details, and depend only on robust features such as the spatial dimension and the symmetry of the ordered phase. This is also true in superconductors; it was argued by Fisher, Fisher, and Huse that near the critical temperature, the AC conductivity of a superconductor should assume a universal scaling form, characterized by two critical exponents and a universal scaling function.

In our recent work,[1] we explicitly verify this scaling ansatz by calculating the conductivity using renormalization group methods. Our calculated scaling function is in reasonable agreement with recent microwave frequency measurements of the AC conductivity of YBCO, carried out by Anlage's group at the University of Maryland.

[1] Wickham, R.A., *et al.,* Phys. Rev. B, **61,** 6945 (2000).

## Upper Critical Field of the Ferromagnetic Superconductor $Gd_{1.4}Ce_{0.6}RuSr_2Cu_2O_{10-\delta}$

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Recently, much attention has been devoted to a phase, resembling $RBa_2Cu_3O_{7-\delta}$ (R=rare earth), having the composition $(R_{1-x}Ce_x)_2MSr_2Cu_2O_{10-\delta}$ (M-2122;

M=Nb, Ru and others).[1,2] The tetragonal Ru-2122 phase crystallizes in a tetragonal structure, space group I4/mmm, and it evolves from $RBa_2Cu_3O_{7-\delta}$ structure by inserting a fluorite type layer $(R_{1-x}Ce_x)_2O_2$ instead of the R layer in the former compound. The hole doping of the $CuO_2$ planes results in metallic behavior and superconductivity (SC) at low temperatures when properly oxidized.[1,2]

On the other hand, the Ru sublattice displays cooperative properties such as weak-ferromagnetism (w-FM) at temperatures relatively higher. More recently, Felner and co-authors[3] have observed that these two phenomena coexist in a large range of temperatures in compounds with stoichiometry close to $(R_{1-x}Ce_x)_2RuSr_2Cu_2O_{10-\delta}$ (R=Gd and Eu; x≈0.25). They found that weak ferromagnetism develops below $T_M$≈180 K and 120 K for Gd and Eu compounds, and that the superconducting critical temperatures $T_c$ were 42 K and 32 K, respectively. This kind of coexistence is a fundamental problem that has been studied both experimentally and theoretically since the early 60's.[4]

It is the aim of this study to contribute to the discussion regarding the superconducting state of these Ru-2122 phases. Within this context, we have prepared high quality polycrystalline samples of $Gd_{1.4}Ce_{0.6}RuSr_2Cu_2O_{10-\delta}$ through sol-gel precursors.[5] The samples were annealed at 900 $^0$C under oxygen pressure as high as 100 atm and were characterized by magnetization, electrical resistivity, and magnetoresistance measurements in applied magnetic fields as high as 18 T.

1 Cava, R.J., *et al.*, Physica C, **191**, 237 (1992).
2 Bauernfeind, L., *et al.,* Physica C, **254**, 151 (1995).
3 Felner, I., *et al.,* Phys. Rev. B, **57**, 550 (1998); Sonin, E.B., *et al.,* Phys. Rev. B, **57**, R14000 (1998); Felner, I., *et al.,* Physica B, **259-261**, 703 (1999); Felner, I., *et al.,* Physica C, **334**, 141 (2000).
4 See, for example, *Superconductivity in Ternary Compounds*, eds. M.B. Maple, *et al.,* (Springer-Verlag, 1982), Vol. II.
5 Jardim, R.F, *et al.,* J. Alloys Compounds, **199**, 105 (1993).

## Two-Component Model and Its Implications for Properties of Cuprates

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Efforts continued to further explore temperature and doping dependencies of the two-component model by Gor`kov and Sokol (1987) to accommodate recent findings in the normal cuprates' properties, such as a giant isotope effect in the so-called pseudo-gap characteristics, namely, in the precursor temperature, T*, and the observation of dynamical "stripes" in experiments covering a broad range of time scales. The two phenomena treated in frameworks of the aforementioned model imply involvement of the non-linear lattice interactions between holes trapped into polaronic states on the copper sites (Cu ion in the d9-configuration). Such an interaction results in the tendency to a first order phase transition, while the Coulomb forces and hybridization lead to formation of inhomogeneous mixture of phases domains fluctuating with time.[1]

1 Gor`kov, L.P., J. Supercond., **13**, 765 (2000).

## Exchange Interaction Between Spins in a Superconductor

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We have studied the exchange interaction between spins in both normal and superconducting phases of a d-wave material. In particular, we have worked out the interaction between the orbital motion of the quasi particles as affected by a spin orbit interaction with the impurity spin. We find that the exchange interaction varies as the inverse square of the distance between impurities in both the normal and superconducting phase. This is stronger than the conventional RKKY interaction for reasonable values of the spin orbit interaction when the impurity spacing is large compared to the inverse Fermi wave vector.

# Normal State Resistance of Single Crystals of $Pr_{1.85}Ce_{0.15}CuO_4$

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A metal-insulator crossover in the temperature dependence of the resistivity of thin-film samples of the electron-doped high-$T_c$ superconductor $Pr_{2-x}Ce_xCuO_4$ has been observed as $x$ is reduced.[1] The insulating behavior is characterized by an upturn in the low temperature resistivity. This is also observed in single crystal samples with $x$=0.15, corresponding to optimal doping with respect to the superconducting transition temperature, once the superconductivity is suppressed by a magnetic field. From measurements made at the University of Toronto, we had established that for fields up to 15 T, the low temperature normal state magnetoresistance was negative, suppressing the upturn. Using the 33 T steady field magnet and a $^3$He cryostat at NHMFL, we investigated the effect of larger magnetic fields on this insulating behavior.

The temperature dependence of the resistivities of two single crystals of $Pr_{1.85}Ce_{0.15}CuO_4$ (PCCO) between 1 to 30 K were measured at constant magnetic fields of 20, 25, and 29 T. The resistivity was measured with the current flowing in the *ab*-plane and the magnetic field applied perpendicular to this plane. The results of these measurements are shown in Figs. 1 and 2 for these samples labelled #4 and #9 respectively. In addition, we measured the low temperature (~ 1 K) magnetoresistance while sweeping the field to 29 T.

For sample #4, a magnetic field of 29 T was sufficient to almost completely suppress the insulating upturn and saturate the negative magnetoresistance. However, the effect of magnetic field on sample #9 was much smaller despite the larger size of the upturn. The differences between these two behaviors may be due to *c*-axis resistivity contributions in sample #9.

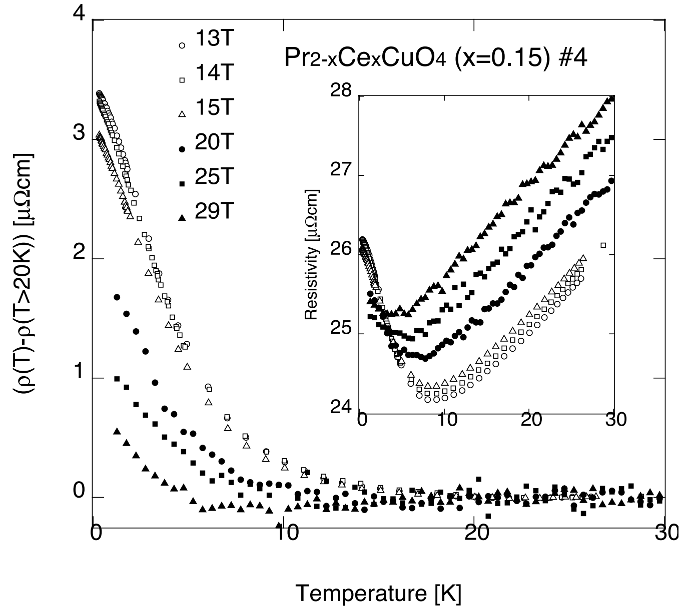


**Figure 1**. Temperature dependence of the resistivity of $Pr_{1.85}Ce_{0.15}CuO_4$ sample #4 at magnetic fields 13 to 29 T, applied perpendicular to the *ab*-plane. Inset shows the raw data. In the main plot, the high temperature (T >20 K) resistivity has been subtracted to reveal more clearly the suppression of the low temperature upturn as the field is increased.

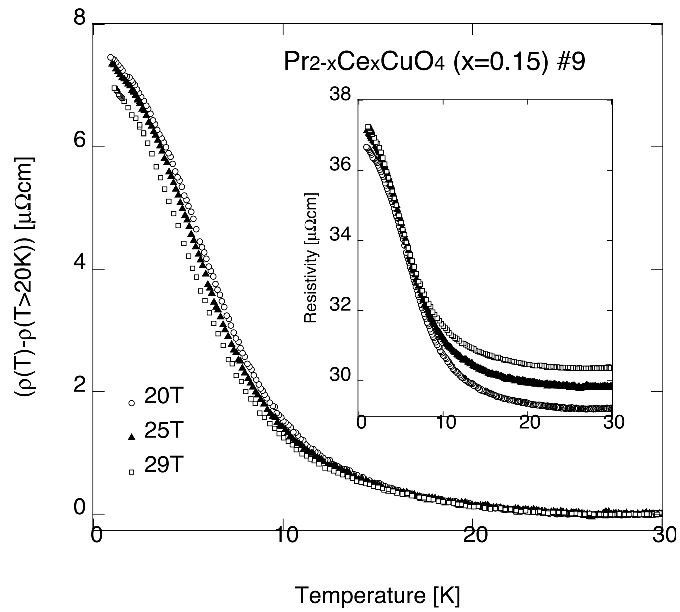


**Figure 2**. Temperature dependence of the resistivity of $Pr_{1.85}Ce_{0.15}CuO_4$ sample #9 at magnetic fields 20, 25, and 29 T, applied perpendicular to the *ab*-plane. Inset shows the raw data. In the main plot, the high temperature (T > 20 K) resistivity has been subtracted to reveal more clearly the suppression of the low temperature upturn as the field is increased.

[1] Fournier, P., *et al*., Phys. Rev. Lett., **81,** 4720-4723 (1998).

## Disorder and Order Parameter Suppression in *d*-wave State

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The low-energy density of states of disordered 2D *d*-wave superconductors is extremely sensitive to symmetries of models of disorder and the electronic spectrum of the metal from which the superconductor condenses. Using traditional diagrammatic methods and large-scale numerical solutions of the Bogoliubov-de Gennes equations, it was shown that the physical origin of this sensitivity is the existence of a novel diffusion mode with momentum (π,π) which does not exist in the normal metal, and is gapless only under very special, unphysical circumstances. Proximity to this special point, which corresponds to the Pépin-Lee divergence in the density of states, will nevertheless lead to observable effects in the cuprates. Self-consistent order parameter suppression was found to lead to a dramatic *suppression* of the impurity-induced density of states near the Fermi energy, in contradiction to the usual "Swiss cheese" picture of small metallic regions around the impurity sites. This effect is possibly analogous to the Coulomb gap in disordered low-dimensional metallic systems.

1 Atkinson, W.A., *et al.,* Phys. Rev. Lett., **85**, 3922 (2000).
2 Atkinson, W.A., *et al.,* Phys. Rev. Lett., **85**, 3926 (2000).

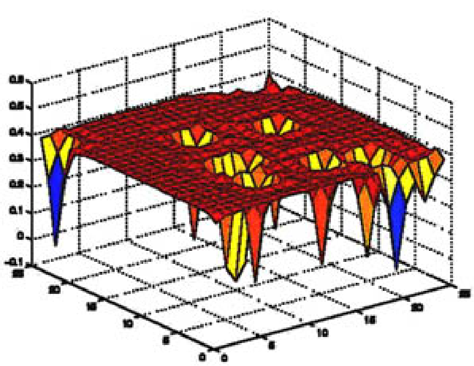

**Figure 1.** Amplitude of *d*-wave order parameter in the presence of random unitary scatterers.

## Semiclassical Theory of a *d*-wave Superconductor in Magnetic Field

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A systematic perturbation theory was developed[1] to describe the magnetic field induced subdominant *s*- and $d_{xy}$-wave order parameters in the mixed state of a $d_{x2-y2}$-wave superconductor, leading to analytic results for the free energy of a *d*-wave superconductor in an applied magnetic field $H_{c1}$<~H<<$H_{c2}$, from $T_c$ down to very low temperatures. Known results for a single isolated vortex in the Ginzburg-Landau regime were recovered, and the behavior at low temperatures for the subdominant component shown to be qualitatively different. In the case of the subdominant $d_{xy}$ pair component, superfluid velocity gradients and an orbital Zeeman effect are shown to compete in determining the vortex state.

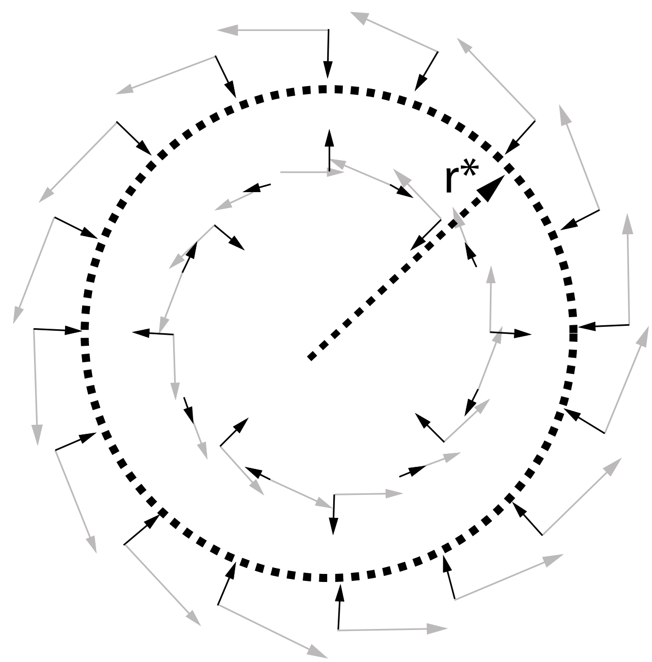


**Figure 1.** Semiclassical solution for single vortex in $d_{x2-y2}$ superconductor with subdominant $d_{xy}$ channel at low T. Relative angle of dark and light arrows indicates relative phase of 2 components.

Semiclassical solution for single vortex in $d_{x2-y2}$ superconductor with subdominant $d_{xy}$ channel at low T. Relative angle of dark and light arrows indicates relative phase of two components.

The semiclassical theory was also generalized[2] from a one-vortex average to an average over a probability distribution of local quasiparticle Doppler shifts, which can be taken to characterize the vortex liquid, glass, or appropriate lattice state. This leads to qualitatively different predictions for thermodynamic properties under some circumstances.

[1] Li, M.R., *et al*., Phys. Rev. B, **63**, 54504 (2001).
[2] Vekhter, I., *et al.,* cond-mat/0011091.

## Electrical Transport Properties of Strongly Underdoped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ Single Crystal Samples Under High Magnetic Field

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One important goal in the studies of high temperature superconductors is developing an understanding of the nature of the normal state. To accomplish this, we used the NHMFL/Los Alamos 60 T pulsed magnet to quench the superconducting state in underdoped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples in order to examine the anisotropic transport properties of the normal state. For this study, we prepared $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal samples with $T_c$ values between 15 to 30 K by flux growth in $Y_2O_3$ stabilized $ZrO_2$ crucibles. A four probe resistivity technique was used to study both ab-plane and c-axis resistivities, $\rho_{ab}$ and $\rho_c$. At temperatures ranging from 0.35 K to 30 K, isothermal $\rho(H)$ curves were measured using a transient digitizer to monitor the fast (10 μs) output of a lock-in amplifier driven at 120 kHz. Detailed analysis of the data will provide new insights into some of the important issues regarding the normal state properties of these underdoped samples, such as dimensionality of the charge carrier localization and the superconductor-insulator transition.

**Acknowledgments:** The authors wish to thank Dr. Jonathan B. Betts and Dr. Charles H. Mielke for their generous assistance and helpful discussions during the experiment.

## Search for Superconductivity Recurrence in $Sr_2RuO_4$ Under High Magnetic Fields

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There is now substantial evidence that the superconducting symmetry of $Sr_2RuO_4$ ($T_c$=1.5 K) is spin triplet.[1] The most probable wave function consists of the spin part $S_z$=0: equal-spin pairing in the $RuO_2$ plane. In that case, the superconductivity restoration may occur under a very large magnetic field (expected to be more than 30 T) precisely parallel to the $RuO_2$ plane, because the paramagnetic depairing as well as the orbital depairing would become ineffective in such configuration.[2] In our previous attempt, we investigated the in-plane, longitudinal magnetoresistance with $\mu_0 H$ // [110] up to 33 T, but did not observe any anomaly suggestive of superconductivity recurrence. In the present pursuit, we have extended our search to other field configuration by resistivity and susceptibility.

For these experiments, it is crucial to apply the magnetic field accurately parallel to the quasi-two-dimensional plane, because otherwise the out-of-plane component of the applied field may exceed the upper critical field $\mu_0 H_{c2}$ // [001]. For this purpose, we developed a piezoelectrically driven sample rotator for use at low temperatures and at high fields (Fig. 1).[4] This rotator, actuated only with two lead wires,

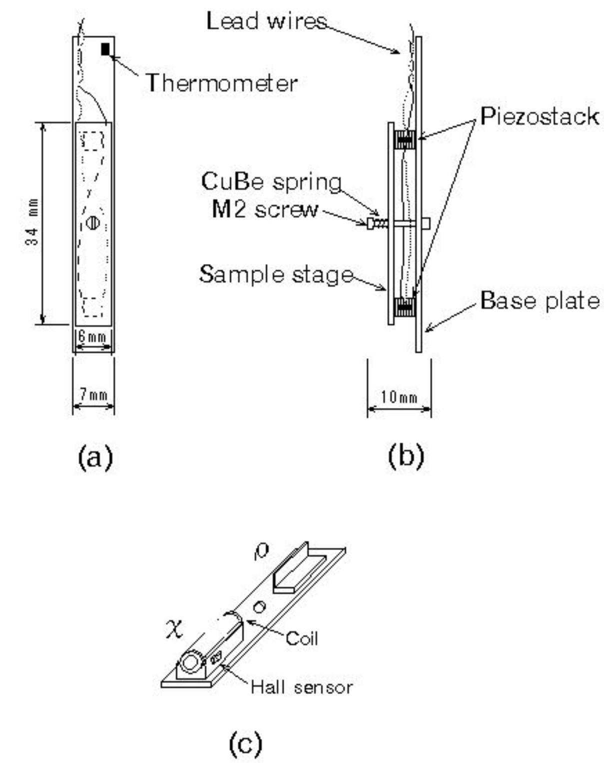


**Figure 1.** Schematics of a piezoelectrically driven rotator: (a) top view, (b) side view, and (c) details of the sample stage with sample holders for resistivity and susceptibility measurements.

instead of a driving shaft, is designed to fit into a narrow sample space with a diameter of 13 mm, and is capable of rotations with a high angular resolution of approximately 0.01°. in magnetic fields reaching 33 T. Since the estimated heat dissipation during rotation is less than 100 μW, it is possible to use it for a continuous rotation in a dilution refrigerator below 100 mK. Moreover, the absence of backlash provides an important advantage over the conventional geared rotator. As a result, the accurate field alignment of the crystals is readily made by utilizing the fact that the upper critical field, $H_{c2}$, is sharply peaked for the field parallel to the $RuO_2$ plane.

Fig. 2 represents the field dependence of the AC susceptibility at 50 mK with both the DC and AC fields along the [100] direction. The accurate alignment of the DC field to the crystalline axis was made. The superconducting transition at $\mu_0 H_{c2}$=1.53 T and the vortex pinning features at slightly lower field are clearly seen. The gradual field dependence at high fields does not entirely represent the signal intrinsic to the crystal. Nevertheless, we did not observe any additional anomalous features up to 33 T, nor did the longitudinal magnetoresistance for $H$ // [100] show any anomalous behavior. We therefore conclude that the superconductivity recurrence does not occur either because of the insufficient field strength or because of the limitation of the applicability of the theory to $Sr_2RuO_4$. Concerning the latter case, the dispersion along the inter-layer direction or the presence of the impurity scattering in the real system[5] may be detrimental to the recurrent superconducting state.

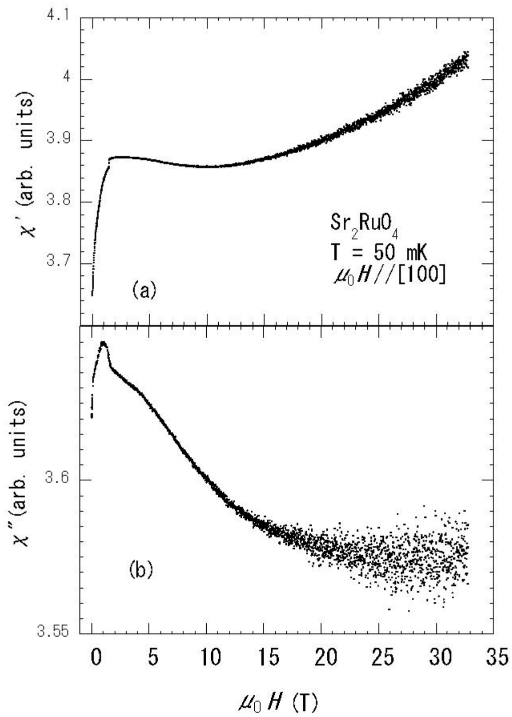


**Figure 2.** AC susceptibility of $Sr_2RuO_4$ under the magnetic field along the in-plane [100] direction: (a) the real component, and (b) the imaginary, dissipative component.

**Acknowledgements:** The authors wish to thank E. Palm and T. Murphy for their assistance during the measurements.

1 Maeno, Y., *et al*., Physics Today, **54**, 42 (2001).
2 Lebed, A.G., *et al.,* Phys. Rev. Lett., **80**, 2697 (1998).
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4 Ohmichi, E., *et al*., to appear in Rev. Sci. Instrum., **72** (3), (2001).
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## Doped Stripes in Models for the Cuprates Emerging from the One-Hole Properties of the Insulator IHRP

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The extended and standard t-J models are computationally studied on ladders and planes, with emphasis on the small J/t region. At couplings compatible with photoemission results for undoped cuprates, half-doped stripes separating pi-shifted antiferromagnetic (AF) domains are found, as in Tranquada's interpretation of neutron experiments. Our main result is that the elementary stripe "building-block" resembles the properties of one hole at small J/t, with robust AF correlations across-the-hole induced by the local tendency of the charge to separate from the spin.[1] This suggests that the seed of half-doped stripes already exists in the unusual properties of the insulating parent compound.

[1] Martins, G., *et al.*, Phys. Rev. B, **60**, R3716 (1999); Martins, G., *et al.*, Phys. Rev. Lett., **84**, 5844 (2000).

## Nature of the Pseudogap in $YBa_2Cu_3O_7$ IHRP

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We report $^{63}Cu$ and $^{17}O$ spin-lattice relaxation rate, $1/T_1$, measurements in different magnetic fields in $YBa_2Cu_3O_7$ near $T_c$. These measurements enable us to test the magnetic field dependence of the pseudogap effect on the spin-spin correlation function in different regions in the Brillouin zone using form factors of different nuclei as filters. This is the first experiment in which studies of the momentum dispersion of the pseudogap behavior between $T_C$ and $T^*$ has been carried out.

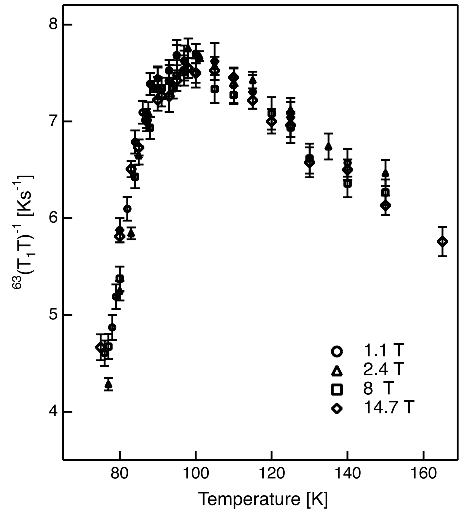


**Figure 1.** Spin-lattice relaxation rate of $^{63}Cu(2)$ in YBCO as a function of temperature in a magnetic field of 1.1, 2.4, 8, and 14.7 T.

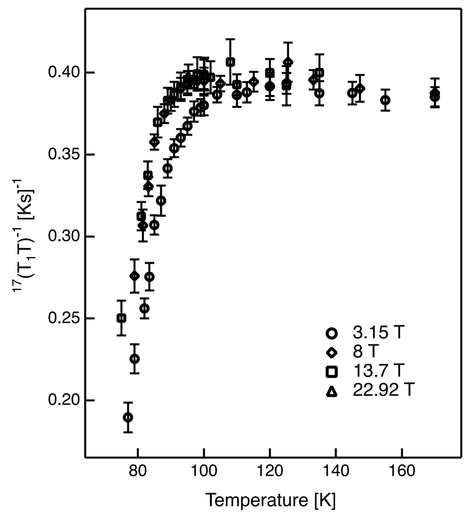


**Figure 2.** Spin-lattice relaxation rate of $^{17}O(2,3)$ in YBCO as a function of temperature in a magnetic field of 3.15, 8, 13.7, and 22.92 T.

In Fig. 1 we show $1/T_1$ of $^{63}Cu$, which probes the imaginary part of the dynamic spin susceptibility, $\chi''$ ($q$, $\omega \rightarrow 0$), near the ($\pi$, $\pi$) point in the Brillouin zone. It shows no magnetic field dependence up to 15 T. This result is consistent with suppression of antiferromagnetic correlations below $T^*$ via a magnetic mechanism as was first indicated by the experiments of Gorny *et al.*[1] From our data we can estimate T* to be ~105 K in near-optimally doped samples.

In Fig. 2 we show $1/T_1$ of $^{17}O$, which probes χ'' (q, ω –> 0) closer to the (0, 0) point in contrast to the copper relaxation. It shows magnetic field dependence on the scale of 10 T for temperatures below 120 K. We account for this increase quantitatively by suppression of the negative contribution to the rate originating from density-of-states superconducting fluctuations with d-wave symmetry.[2] This result shows that away from the (π, π) point the nuclear relaxation is dominated by a Fermi-liquid like susceptibility having a pairing pseudogap, with an energy scale of ~10 T, arising as a precursor to superconductivity.

**Acknowledgements**: Work at Northwestern University is supported by the NSF (DMR 91-20000) through the STCS. The NHMFL is supported through the NSF and the state of Florida.

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1 Gorny, K.*, et al.,* Phys. Rev. Lett., **82**, 177 (1999).
2 Mitrovic, V.F.*, et al.,* Phys. Rev. Lett., **82**, 2784 (1999).

## Out of Plane Transport in the Layered High-$T_c$ $Bi_2Sr_{2-x}CaCu_2O_8$ Investigated in 60 T Magnetic Fields

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Anomalous properties of layered high-$T_c$ cuprates, such as $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Bi-2201), challenge principal foundations of modern condensed matter physics. One of the striking and unexplained paradoxes is the possibility of coexistence of metallic-like conduction inside the layers comprised of copper and oxygen atoms and the insulator-like behavior for the out of plane transport, as has been observed above the superconducting transition temperature, $T_c$. Recently the study of the normal state transport properties has been extended to temperatures well below $T_c$ by suppressing the superconductivity with 60 T pulsed magnetic fields.[1-3] In this report we present the out of plane (*c*-axis) transport properties of the Bi-2201 investigated in high magnetic fields down to 0.5 K over a wide range of carrier concentrations.

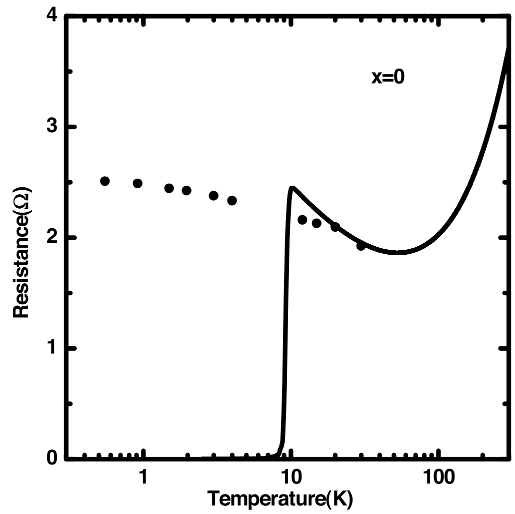


**Figure 1.** *T* dependence of $\rho_c$ of the $Bi_2Sr_2CuO_{6+\delta}$ crystal in 0 T (solid lines) and 60 T (symbols).

The single crystals of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ are grown for this experiment using a floating-zone technique for a wide range of La concentration *x*, from *x*=0 (overdoped) to 0.8 (heavily underdoped)[4]. The resistivity is measured in the longitudinal geometry, with both current and magnetic field along the *c*-axis ($I \parallel B \parallel c$). Fig. 1 shows the *T* dependence of $\rho_c$ in 0 T and 60 T for *x*=0. The data for x=0.8 is presented in Fig. 2.

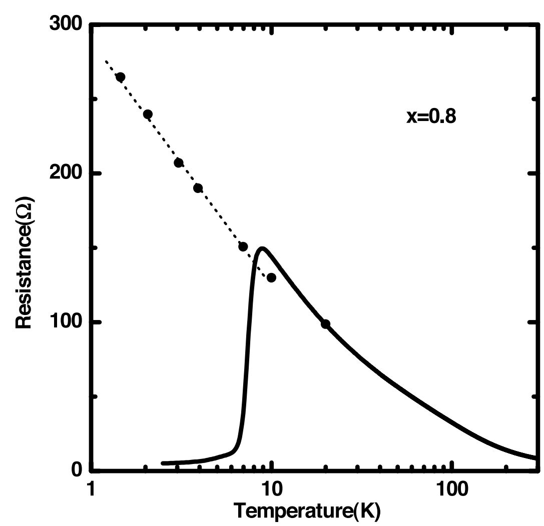


**Figure 2.** *T* dependence of $\rho_c$ of the $Bi_2Sr_{1.2}La_{0.8}CuO_{6+\delta}$ crystal in 0 T (solid lines) and 60 T (symbols). The straight line emphasizes the log(1/T) behavior.

In zero field, both samples show insulating behavior ($d\rho_c/dT < 0$) above $T_c$. When superconductivity is suppressed with 60 T field, the insulating behavior clearly saturates in the overdoped sample (x=0). The underdoped sample (x=0.8) shows no signs of saturation in the insulating behavior. We also note that the $\rho_c(T)$ of the underdoped sample increases as log (1/T) with decreasing temperature. Similar and still unexplained log (1/T) divergence of the in-plane resistivity has been observed in underdoped Bi-2201[3] and $La_{2-x}Sr_xCuO_4$.[1]

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1 Ando, Y., *et al.*, Phys. Rev. Lett., **75**, 4662 (1995).
2 Boebinger, G.S., *et al.*, Phys. Rev. Lett., **77**, 5417 (1996).
3 Ono, S., *et al.*, Phys. Rev. Lett., **85**, 638 (2000).
4 Ando, Y., *et al.*, Phys. Rev. B, **60**, R6991 (1999).

## Angle Dependence of the Cyclotron Resonances in $Sr_2RuO_4$


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We have carried out angle dependent studies of the normal state microwave (40 to 120 GHz) magneto-conductivity of several single crystal samples of the perovskite superconductor $Sr_2RuO_4$. As previously reported (*1999 NHMFL Annual Research Review*, and Ref. 1), we observed a series of resonant absorptions which we attribute to cyclotron resonance

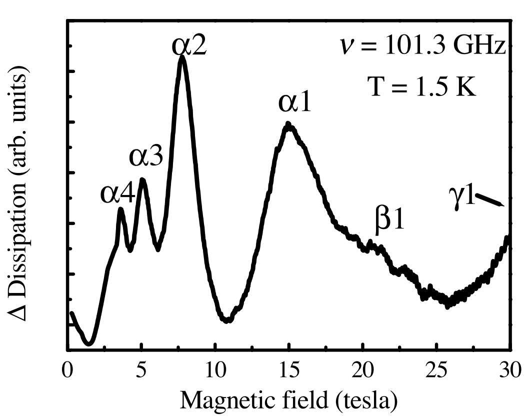


**Figure 1.** Raw cyclotron resonance absorptions.

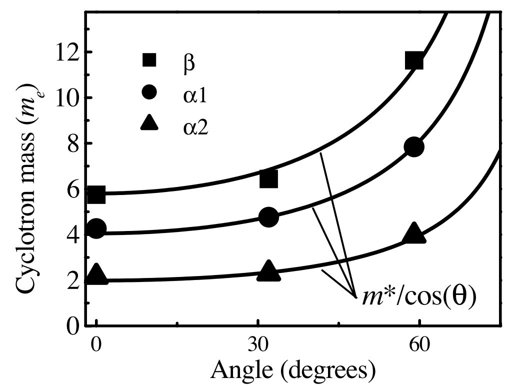


**Figure 2.** Angle dependence of the obtained cyclotron effective masses.

of quasiparticles belonging to the three well known Fermi surfaces for this material. Fig. 1 shows raw data obtained at a frequency of 101.3 GHz. Several resonances are observed corresponding to the α (plus its harmonics, α2, etc.), β, and γ pockets. The apparent increase in noise at high fields actually corresponds to the onset of Shubnikov-de Haas oscillations, which may be used to accurately determine the orientation of the sample with respect to the applied magnetic field.

From the angle dependence (Fig. 2), which was lacking in the previous study, we confirm the two-dimensional character of these resonances, *i.e.,* the cyclotron frequencies scale as the cosine of the angle between the magnetic field and the normal to the conducting layers. Furthermore, by performing measurements on several samples in different electromagnetic field configurations, we are able to couple to different cyclotron modes (+ harmonics) that derive from deformations (warpings) of the Fermi surfaces from perfect cylinders, thereby confirming the mechanism proposed for resonant absorption proposed in our original study.[1] Our findings also appear to be in excellent agreement with recent angle dependent de Haas-van Alphen measurements by Bergemann *et al.*,[2] which provide complementary information to these studies. Finally, comparisons between the effective masses deduced from this and other techniques[2] provide us with a unique means of gauging the role of Coulomb correlations in this compound.

**Acknowledgements:** This work was supported by NSF DMR 0071953, Research Corporation and the Office of Naval Research (N00014-98-1-0538).

[1] Hill, S., *et al*., Phys. Rev. Lett., **84**, 3374 (2000).
[2] Bergemann, *et al*., Phys. Rev. Lett., **84**, 2662 (2000).

## Anomalous Behavior of Spin Fluctuations in Polycrystalline $NdBa_2Cu_3O_7$

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It is well known that substitution of a rare-earth (RE) magnetic ion to Y in $YBa_2Cu_3O_7$ produces little or no effect in transition temperature $T_c$. The interplay between magnetism and superconductivity in these materials have been controversial and NMR have played an important role in its theoretical understanding. In this light, an $^{17}O$ NMR study of $NdBa_2Cu_3O_7$ was recently undertaken with some unexpected results. The Nd ions have localized moments and orders antiferromagnetically at $T_N \sim 0.5$ K, but the $T_c$ of $NdBa_2Cu_3O_7$ remains at 92 K. Unlike most RE, the Nd ion is too large to fit in the lattice and tends to occupy the Ba site; the only other case being $PrBa_2Cu_3O_7$. The $^{17}O$ NMR spectra and spin-lattice relaxation time $T_1$ of magnetically aligned polycrystals were measured for two different O sites as a function of temperature at different magnetic fields, including 37 T in the hybrid magnet. Fig. 1 shows $T_1$ vs. 1/T at various fields for the planar O(2,3) sites.

There are several features to note: (a) extremely fast relaxation—the $T_1$ is nearly 2 orders of magnitude shorter than that of $YBa_2Cu_3O_7$; (b) there is no evidence of the "pseudogap" above $T_c$ nor a signature of superconducting transition at $T_c$; and (c) there is an anomalous field-dependent minimum in $T_1$ which lies well below $T_c$ and much above $T_N$. The Cu NMR in this system is not observable due to short $T_1$. This fast relaxation is almost certainly due to Nd spin fluctuations which, in addition to Cu, contributes significantly and possibly dominates and masks the pseudo-gap because of its large moment.

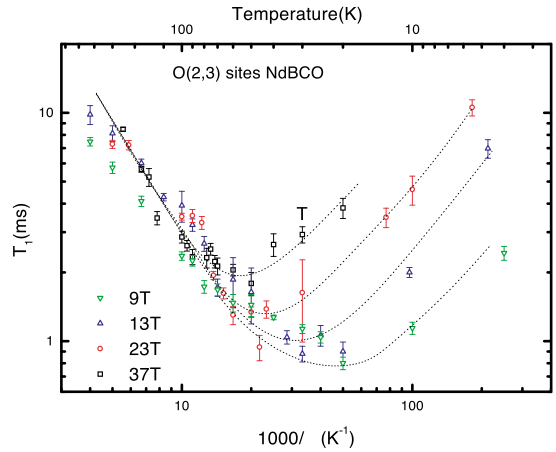


**Figure 1.** Plot of $T_1$ vs. 1/T for $^{17}O$ NMR at the O(2,3) sites in $NdBa_2Cu_3O_7$ for various fields. Lines are guides to the eye.

The minimum in $T_1$ below $T_c$ has not been observed in other cuprate superconductors. The physical origin of this behavior is unexpected considering the fact that the antiferromagnetic ordering of the Nd occurs more than an order of magnitude lower in temperature. Typically, $T_1$ minimum (or a peak in rate $1/T_1$) is understood as a signature of critical slowing down, and possibly "freezing," of the spin fluctuations. The minimum therefore corresponds to $\omega\tau_c \sim 1$, where $\tau_c$ is the correlation time of the Nd spins and  is the NMR frequency. In this picture, the field dependence originates from the behavior of spin-fluctuation power spectrum beyond the $1/\tau_c$ cutoff, which goes as $\propto \omega^2$. The magnitudes of $T_1$, at temperatures below the minimum qualitatively scale with field as expected from this speculation. However, data on the apical $O_4$ site (not shown) also shows a minimum in $T_1$ at about 20 K which, however, is somewhat less field independent, and thus appears inconsistent with the speculations as to the mechanism. On the other hand, the O(4) is much more weakly coupled to the Nd than the O(2,3), as indicated by the almost one order of magnitude longer $T_1$, and may possibly have considerable contribution from Cu.

This phenomenon, while probably unimportant to the superconductivity, raises interesting questions as to how, in spite of a very tight coupling of the charge and spin in this system, the critical balance with magnetism is maintained to preserve superconductivity.

# The Angle Dependence of the Magneto-Optical Response of the Exotic Superconductor $Sr_2RuO_4$

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The layered correlated-electron system $Sr_2RuO_4$ has generated much interest, both theoretical and experimental. A large number of data suggest that its superconductivity is ferromagnetically-mediated, leading to a spin-triplet p- or f-wave groundstate.[1,2] It is of great interest to be able to make reliable measurements of cyclotron resonance (CR)[3,4] in this material; contributions to the effective mass renormalization from electron-electron interactions and electron-phonon interactions can be separated by comparing the mass measured by CR with the effective mass found in thermodynamic measurements.[4] Recently, a measurement of CR in $Sr_2RuO_4$ has been reported.[3] In that study, however, there was no measurement of the dependence of the observed resonances on magnetic field orientation; measurement of the angle-dependence has been shown to be important in other low-dimensional systems.[5]

We have used a unique cryostat, built in Oxford, to measure the magnetic-field-orientation dependence of the millimeter-wave magneto-optical response of $Sr_2RuO_4$. The cryostat allows a rectangular resonant cavity containing the sample to be rotated within the static magnetic field; hence, the millimeter-wave environment of the sample remains the same even when it is tilted within the static field.[5] Fig. 1 shows the angle dependence of the various magneto-optical resonances observed as a function of θ, the angle between the quasi-two-dimensional planes and the magnetic field; the temperature was 500 mK, the frequency was 70.2 GHz, and magnetic fields were provided by the 33 T Bitter coil at the NHMFL in Tallahassee. The positions of the resonances are shown in inverse-field units; conventional CR associated with the quasi-two-dimensional Fermi surface sections should follow a cosθ dependence. At small θ, the spectrum is dominated by the fundamental, second, third, and fourth harmonics (filled diamonds) of a CR associated with the β Fermi-surface cylinder; the corresponding mass is 4.3 $m_e$. As θ increases, the odd harmonics (3, 5, 7, 9- hollow circles) of another CR (mass 12.4 $m_e$), associated with the γ cylinder, are observed. Finally, the fundamental CR associated with the α cylinder is also seen (filled stars), with mass 5.6 $m_e$. Further resonances (filled squares, filled circles) behave in quite different ways with θ and can be associated with the combined effect of the corrugations of the various Fermi-surface sections.[6]

A comparison of the masses derived from the present CR experiment and the de Haas-van Alphen effect is in agreement with current theoretical expectations

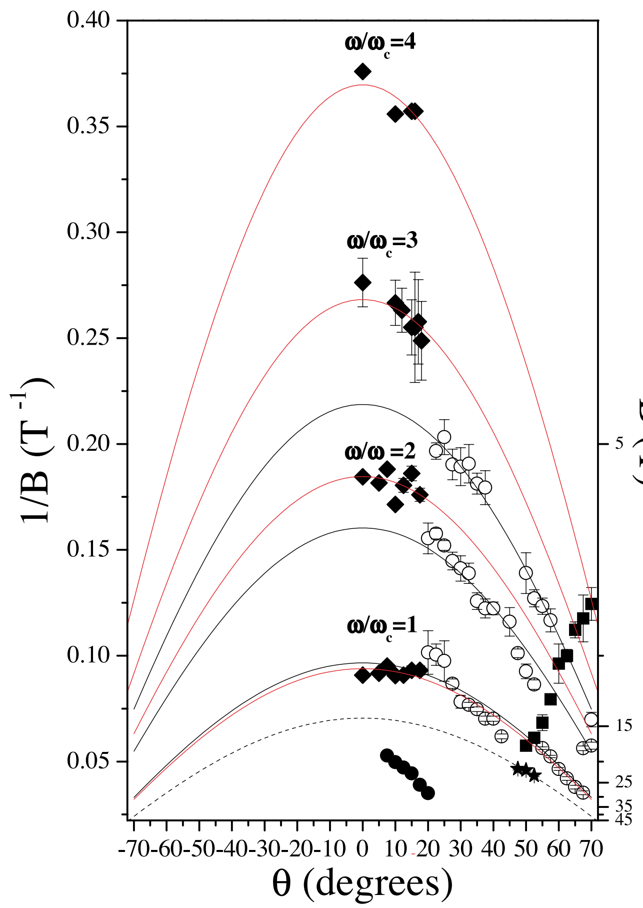


**Figure 1.** The positions of resonances (in inverse-field) are plotted as a function of polar angle, θ. The points indicate experimental data, different styles of points identifying different origins for the resonance (see text). The solid lines represent the cosθ dependence expected for quasi-two-dimensional cyclotron resonances.

once the effects of band filling are taken into account.[7] Our data also show that the magnetic orientation dependence of the CRs is vital in order to identify their origin; there is no doubt that some of the masses in Ref. 3 are incorrect because an orientation dependence was not carried out.


1 Maeno, Y., Physica C, **282-287**, 206 (1997).
2 Bergemann, C., *et al*., Phys. Rev. Lett., **84**, 2662 (2000).
3 Hill, S., *et al*., Phys. Rev. Lett., **84**, 3374 (2000).
4 Singleton, J., *et al*., Rep. Progr. Phys., **63**, 1111 (2000).
5 Ardavan, A., *et al*. Phys. Rev. Lett., **81**, 713 (1998).
6 Rzepniewski, E., *et al.,* submitted.
7 Kanki, K., *et al*., J. Phys. Soc. Jpn., **66**, 1103 (1997).


## c-Axis Transport in the Double-Layered $Bi_2Sr_{2-x}CaCu_2O_{8+\delta}$ in 60 T Pulsed Magnetic Fields


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Considerable interest surrounds the study of the normal state of the high-$T_c$ cuprates at low temperatures, as revealed when intense magnetic fields suppress the superconducting state. Detailed studies to date have been limited to cuprates which exhibit relatively low superconducting transition temperature, $T_c$, such as $La_{2-x}Sr_xCuO_4$ (LSCO) [1,2] and $Bi_2Sr_{2-x}LaxCuO_{6+\delta}$ (Bi-2201),[3] because the superconductivity is readily suppressed by a 60 T pulsed magnetic field in these compounds with a maximum $T_c$ ~ 40K. Double-layer $Bi_2Sr_{2-x}CaCu_2O_{8+\delta}$, by contrast, exhibits a maximum $T_c$ ~85K. Preliminary investigations on double-layer $Bi_2Sr_{2-x}CaCu_2O_{8+\delta}$ have indicated the degree to which superconductivity can be suppressed in this compound as a function of the carrier concentration. This information will be used in planning future experiments at the NHMFL.


1 Ando, Y., *et al*., Phys. Rev. Lett., **75**, 4662 (1995).
2 Boebinger, G.S., *et al*., Phys. Rev. Lett., **77**, 5417 (1996).
3 Ono, S., *et al*., Phys. Rev. Lett., **85**, 638 (2000)


## Pairing Polarons in High Temperature Superconductors


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We have studied the nature of a quasi particle in a superconductor. In contrast to low temperature superconductors, high $T_c$ materials exhibit a strong decrease of the order parameter in the vicinity of a quasi particle producing a pairing polaron. We find that as quasi particles are added to the system they form domain walls on which the excitations live. This leads to a band of states near the midgap. The phase of the order parameter changes by 180° as one crosses the boundary. The infrared absorption exhibits anomalous peaks in the presence of the quasi particles. The analysis was carried out for parallel spin excitations. This can be achieved by injecting quasi particles from a spin polarized source.

## Closing the Pseudogap by Zeeman Splitting in $Bi_2Sr_2CaCu_2O_{8+y}$ at High Magnetic Fields


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Li, M., Leiden Univ., Kamerling Onnes Laboratory
Maley, M.P., LANL
Kes, P.H., Leiden Univ., Kamerling Onnes Laboratory


Current knowledge about the field dependence of the pseudogap in the normal state of high temperature superconductors is partly limited by the available DC field range. More importantly, there is no systematic doping dependence in a single family of cuprates. We report the interlayer ($c$-axis) resistivity $\rho_c$ measurements in fields up to 60 T using a long pulse (LP) system and a 33 T DC system at the NHMFL in $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) crystals in a wide range of doping. From these experiments, we make a first systematic evaluation of the pseudogap closing field $H_{pg}$ that restores low-energy density of state (DOS) to its ungapped state. Our results indicate a pronounced difference between field-temperature diagrams of the pseudogap and the superconducting states and a simple Zeeman scaling between $H_{pg}$ (0) and the pseudogap temperature T*.

In slightly underdoped BSCCO at temperatures below $T_c$, the field dependence of $\rho_c$ exhibits a peak that we have previously demonstrated to arise from a competition between two tunneling conduction channels: Cooper pairs (at low fields) and quasiparticles (mainly at high fields).[1] The peak position $H_{sc}$ marks the field (in the superconducting state) where the quasiparticle contribution overtakes the Cooper pair tunneling current. The doping dependence of $\rho_c$ clearly shows that the peak field $H_{sc}$ in the highly underdoped crystal, where interlayer (Josephson) coupling is the weakest, is most easily suppressed. Magnetoresistance (MR) above $H_{sc}$ is negative and remains so above $T_c$. In the overdoped samples, negative MR eventually disappears. This occurs at the same temperature at which the zero-field $\rho_c(T)$ develops a characteristic upturn from the T-linear dependence of the metallic state. This temperature is identified as the pseudogap temperature T*. The negative MR below T* is naturally understood by the suppression of the pseudogap by magnetic field. In our most overdoped crystal with $T_c$ = 67 K, a magnetic field of 60 T downshifts the $\rho_c(T)$ upturn and the associated T* by about 20 K. In other words, at this doping level, the 60 T field at ~100 K closes the pseudogap. To track the pseudogap closing field at lower temperatures, we consider the excess resistivity $\Delta\rho_c$ due to the DOS depletion by subtracting the metallic contribution. The field at which $\Delta\rho_c$ vanishes is the pseudogap closing field $H_{pg}(T)$. A fit to the power-law field dependence of $\Delta\rho_c(H)$ at different temperatures allows us to evaluate $H_{pg}(T)$ beyond 60 T.

The entire H-T diagram of the pseudogap in the overdoped crystal is shown in Fig. 1. At low temperatures $H_{pg}$ is essentially flat with the limiting value of ~90 T. This is in marked contrast with the characteristic fields of the superconducting state: the peak field $H_{sc}(T)$ and the irreversibility field $H_{irr}(T)$. This difference may indicate different origins of the pseudo- and superconducting gaps. The doping dependence of the low-temperature $H_{pg}$ and the zero-field T* leads to a strikingly simple

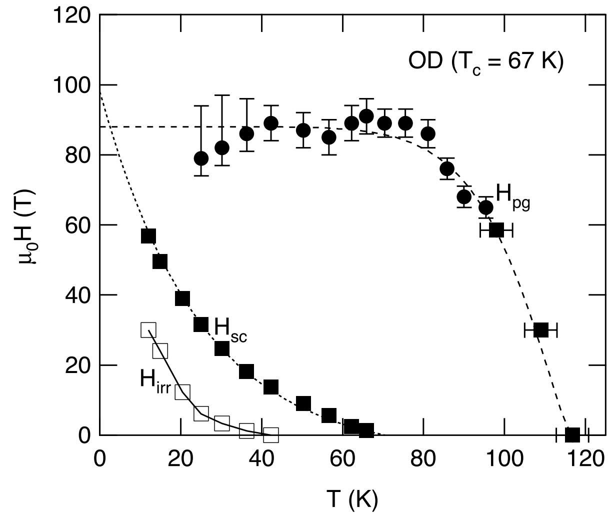


**Figure 1.** H-T diagram showing the pseudogap closing field $H_{pg}(T)$, the peak field $H_{sc}(T)$, and the irreversibility field $H_{irr}(T)$ in an overdoped BSCCO. Up to 60 T, $H_{pg}(T)$ is directly determined from the down-shifting upturn of $\rho_c(T)$ (squares). At lower temperatures, $H_{pg}(T)$ is obtained by extrapolating $\Delta\rho_c(H)$ to zero. The two procedures consistently produce a seamless $H_{pg}(T)$ within the error bars.

conclusion. The pseudogap closing field scales with T* as $g\mu_B H_{pg} \sim k_B T^*$. Here g=2.0, $\mu_B$ is the Bohr magneton, and $k_B$ is the Boltzmann constant. This immediately suggests that magnetic field couples to the pseudogap by the Zeeman energy of the spin degrees of freedom. Our finding that Zeeman splitting closes the pseudogap implies that the triplet spin excitation at high fields overcomes the singlet pair correlations responsible for the gap in the spin spectrum, and that the orbital contribution is very small.

**Acknowledgments:** We thank N. Morozov, F.F. Balakirev, J. Betts, C.H. Mielke, and B.L. Brandt for technical assistance, and L.N. Bulaevskii, N. Nagaosa, V.B. Geshkenbein, L.B. Ioffe, C.C. Tsuei, and D.M. Newns for helpful discussions. This work was supported in part by NSF through NHMFL by the Contract No. AL99424-A009.

[1] Morozov, N., *et al.*, Phys. Rev. Lett, **84**, 1784-1787 (2000).

# Phase Diagram of the Fulde-Ferrell-Larkin-Ovchinnikov State in the Organic Superconductor κ-(BEDT-TTF)$_2$Cu(SCN)$_2$

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We have made careful measurements of the phase diagram of the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state in the organic superconductor κ-(BEDT-TTF)$_2$Cu(SCN)$_2$.[1] Single crystals were mounted within the coil of a tuned circuit differential susceptometer (TCDS). In the TCDS, the coil is part of a tuned circuit operating at ~3 MHz. Changes in the magnetization and the differential susceptibility of the sample are detected as shifts in the frequency. The sample magnetoresistance was measured simultaneously. Samples were aligned with the field (provided by a 33 T Bitter coil at the NHMFL in Tallahassee) parallel to the highly conducting planes to within 0.1°. Several samples were studied to eliminate non-intrinsic effects such as the "synchronization pinning scenario".[1]

In a metal in a high magnetic field, the normal quasiparticals have separate spin-up and spin-down Fermi surfaces which are displaced due to the Zeeman interaction. In the FFLO state, there is an attractive interaction between carriers with opposite spins on opposite sides of the Fermi surface, which leads to the formation of pairs with non-zero total momentum.[1,2,3] The non-zero total momentum leads to a spatial modulation of the superconducting state; this in turn, results in a change in the vortex stiffness on entering the FFLO state that we detect using the TCDS.[1] We label the field at which the stiffness change occurs $B_L$.

Fig. 1 shows the temperature dependence of the upper critical field, $B_p$, determined from the sample magnetoresistance and, $B_L$, plotted alongside a theoretical phase diagram for the FFLO state.[4] The data in the figure bear a strong resemblance to the theoretical phase diagram, and the phase boundaries are independent of the sample used or its history. Moving away from the in-plane geometry allows the number of closed quasiparticle orbits to increase, and so orbital mechanisms destroy the superconductivity. The drop in the response of the TCDS is only clearly visible when the field is within 1.5° of parallel to the conducting layers, in agreement with theoretical expectations.[1]

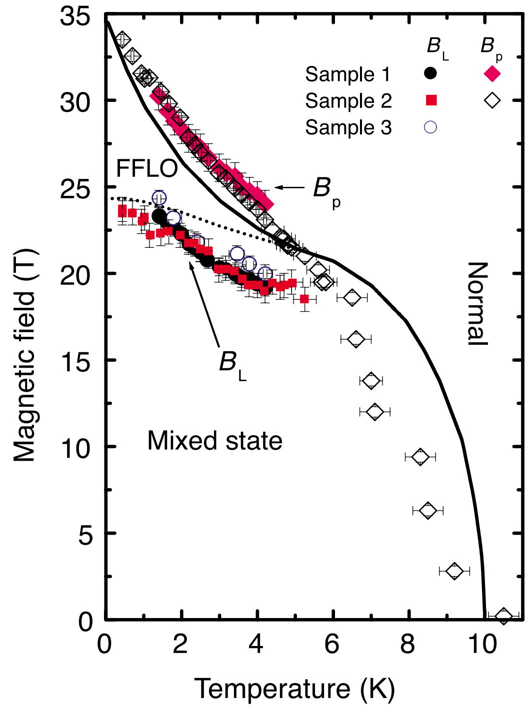


**Figure 1.** Phase diagram of the Fulde-Ferrell-Larkin-Ovchinnikov state in the organic superconductor κ-(BEDT-TTF)$_2$Cu(SCN)$_{2.}$ Temperature dependence of the fields $B_L$ and $B_p$ compared with the theoretical FFLO phase diagram of Reference 4.

[1] Singleton, J., *et al.,* J. Phys. Condens. Matter **12,** L641 (2000).
[2] Fulde, P., *et al*., Phys, Rev., **135,** A550, (1964).
[3] Larkin, I., *et al.,* Zh. Eksp. Teor. Fiz, **47**, 1136, (1964).
[4] Shimahara, H., Phys. Rev. B, **50**, 12760, (1994).

# Detailed Fermi-Surface Topology Studies of the Superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ and Its Close Relatives

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There is considerable interest in the nature of superconductivity in quasi-two-dimensional charge-transfer salts.[1] Several theories stress the importance of the details of the Fermi-surface topology in providing suitable prerequisites for superconductivity. The exact form of the quasi-one-dimensional (Q1D) sheets of the Fermi surface, and in particular their nestability, is important in deciding whether antiferromagnetic fluctuations play a role. In this context, we have used Fermi-surface traversal resonances[1] (FTRs) to map out the corrugations of the Q1D sheets of the layered organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$.[1] We have measured two new corrugations of the Fermi surface which have been previously undetected;[2] a schematic representation of the Fermi-surface sections is shown in Fig. 1 (corrugations exaggerated for clarity).[2] Such detailed information can be used in theoretical models of the antiferromagnetic fluctuations.

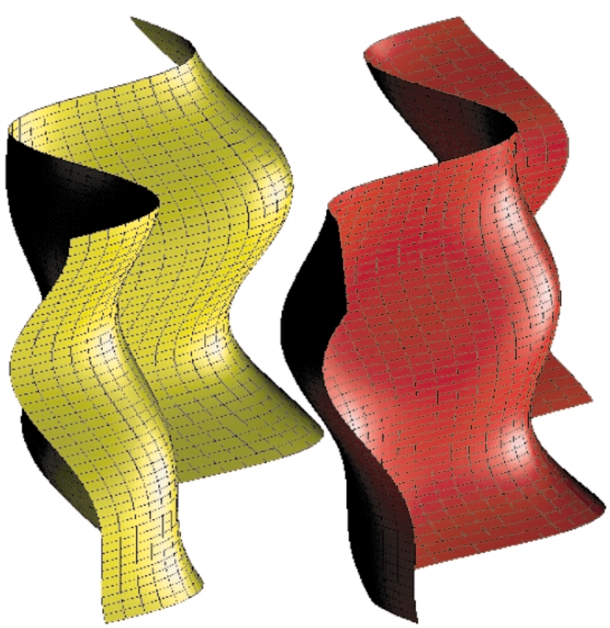

**Figure 1.** Schematic of the corrugated Q1D Fermi sheets of the organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$. The corrugations, which were measured using FTRs, have been greatly exaggerated for clarity; two previously unsuspected corrugation components are immediately obvious.

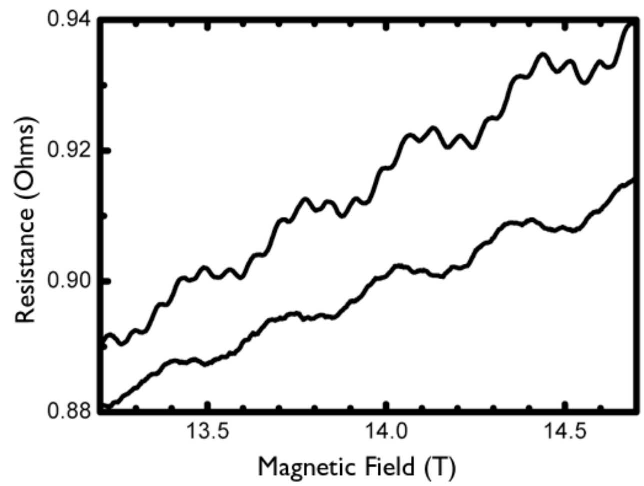


**Figure 2.** Comparison of the low-field Shubnikov-de Haas oscillations in deuterated (top trace) and undeuterated samples of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$. The temperature is 1.03 K. The Stark-Shiba-Fukuyama effect and magnetic breakdown cause the higher frequency oscillations which are very prominent in the deuterated sample.

The isotope effect in organic superconductors is also of great importance.[3-5] After years of effort, the Argonne team has identified a small but significant isotope effect in kappa-phase BEDT-TTF salts.[4,5] There are two possible explanations for this; either the heavier isotopes cause some softening of a mode vital for superconductivity (BCS-type interpretation) or the heavier isotopes apply effective pressure or strain via the anharmonic molecular bonds, resulting in a change in bandstructure which changes the efficiency of paramagnon formation (d-wave explanation). The Argonne team has provided Oxford scientists with samples of several isotopically-substituted BEDT-TTF salts, and careful comparative studies of the magnetic quantum oscillations and FTRs are being undertaken. Fig. 2 shows an example of this work.[3] The upper trace shows low-field Shubnikov-de Haas oscillations in a deuterated (d8) sample of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$, and the lower trace is a simultaneous measurement of a similar sample with hydrogen (h8), rather than deuterium, at the ends of the BEDT-TTF molecules. The consequences of small changes in the Fermi-surface topology brought about by the deuteration are immediately noticeable in the data; the magnetic breakdown and Stark-Shiba-Fukuyama oscillations are much more prominent in the (d8) sample. These studies tend to support the d-wave explanation of the isotope effect.

[1] For a review, see Singleton, J., Rep. Progr. Phys., **63**, 1111 (2000).
[2] Schrama, J.M., *et al.,* J. Phys.: Condens. Matter, in press.
[3] Symington, J.A., *et al.,* submitted.
[4] Kini, A.M., *et al,* Synth Metals, **85**, 1617 (1997).
[5] Schlueter, J.A., *et al.*, Physica B, in press.

## Theoretical Studies of Fulde-Ferrell-Larkin-Ovchinnikov State in Unconventional Superconductors

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It was suggested more than thirty years ago by Fulde and Ferrell,[1] and Larkin and Ovchinnikov,[2] that an inhomogeneous superconductor with an order parameter that oscillates spatially may be stabilized by a large external magnetic or internal exchange field. While never observed in conventional low-$T_c$ superconductors before, this FFLO state has attracted renewed interest in the context of organic, heavy-fermion, and high-$T_c$ cuprate superconductors, which are believed to provide conditions that are favorable to the formation of FFLO state, because many of them are strongly type II superconductors and layered compounds. Indeed, some experimental indications of the existence of the FFLO state have been reported recently[3] in these systems.

Motivated by these, we have been performing theoretical studies on the FFLO states. We have made progress in two different directions. Firstly, we have been studying the effects of non-magnetic impurities on the FFLO state that is formed in superconductors with unconventional pairing symmetry (non *s*-wave). This is useful since most of the candidate systems for the FFLO state currently being studied experimentally are believed to have unconventional pairing symmetry. We do so by calculating the Ginsburg-Landau free energy functional of the system, in the presence of both a large Zeeman splitting and impurity potential. We find the presence of impurities can lead to a phase diagram for the system that is qualitatively different from those previously derived for *s*-wave superconductors; in particular, we find the FFLO state is more likely to survive in the presence of disorder in unconventional than in *s*-wave superconductors. We also find that the structure of the order parameter in the FFLO state, as well as the nature of the phase transition between the FFLO state and the normal state, can be very different in unconventional and *s*-wave superconductors. A paper based on this work[4] has been submitted for publication.

Secondly, an attempt has been made to go beyond mean-field theory in our description of the FFLO state. All previous studies of the FFLO state have been based on mean-field theory. Here, we make the attempt to go beyond the simple mean-field theory by studying the FFLO state in quasi-one-dimensional (Q1D) superconductors. In our study, we treat the intrachain electron-electron interaction exactly using bosonization, while tackling the effects of intrachain coupling using a combination of renormalization group analysis and mean-field approximation. Our results are therefore asymptotically exact in the limit of weak intrachain coupling. We were able to obtain the phase diagram of the system being studied, and address the nature of the phase transition between the phases involved. In particular, we find the transition between the BCS and FFLO phases is a second-order transition of the commensurate-incommensurate type, in contrast to previous studies that suggested this is a first-order transition.

[1] Fulde, P., *et al.*, Phys. Rev., **135**, A550 (1964).
[2] Larkin, A.I., *et al*., Sov. Phys. JETP, **20**, 762 (1965).
[3] See, *e.g.*, Gloos, K., *et al.*, Phys. Rev. Lett., **70**, 501 (1993); Modler, R., *et al*., Phys. Rev. Lett., **76**, 1292 (1996).
[4] Agterberg, D.F, *et al*., cond-mat/0006344.

# Characterizing the Pseudogap Using High Magnetic Fields: Implications on the Phase Diagram of the High-$T_c$ Superconductors

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In the high temperature superconducting cuprates, there exists a crossover boundary in the phase diagram of temperature ($T$)- doping level ($x$) below which low energy spectral weight is lost, hence, *e.g.,* the dynamical spin susceptibility decreases with decreasing $T$. This "pseudogap (PG)" phenomenon has attracted much attention in recent years because it might be related to the mechanism of high-$T_c$ superconductivity. However, the topology of this crossover in the phase diagram and its origin, which are important for narrowing down various theoretical proposals, are still controversial. We have used high magnetic fields to characterize the PG in both underdoped and overdoped regimes. From NMR measurements, we find that the PG in the slightly-overdoped high-$T_c$ superconductor $TlSr_2CaCu_2O_{6.8}$ is strongly magnetic field dependent (Fig. 1), and follows a scaling relation which is shown to be due to Cooper pair density fluctuations.[1] By contrast, the PG in the underdoped $YBa_2Cu_4O_8$ does not depend on fields up to 28.5 T (Fig. 2).[2] Our results suggest that there exists a field-insensitive PG up to a certain doping level before entering the overdoped regime beyond which it is taken over by a superconducting fluctuations-induced one (Fig. 3).[3]

This work was done in collaboration with H. Ozaki, Y. Kitaoka, Y. Kodama and Y. Kubo.

[1] Zheng, G.-Q., *et al.,* Phys. Rev. Lett., **85,** 405-408 (2000).
[2] Zheng, G.-Q., *et al.,* Phys. Rev. B, **60**, R9947-9950 (1999).
[3] Zheng, G.-Q., *et al.,* Physica C, **341-348**, 819-822 (2000).

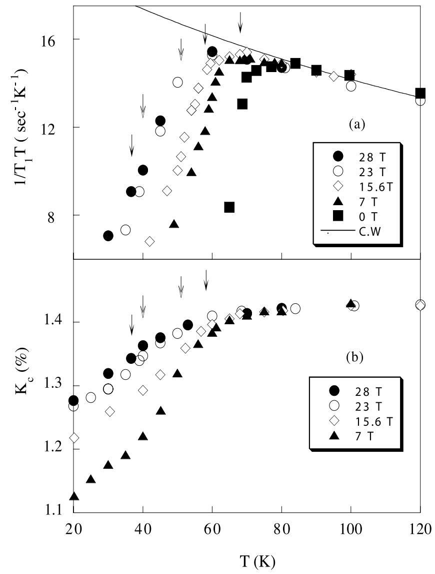


**Figure 1.** Field dependence of the $^{63}$Cu spin-lattice relaxation rate $1/T_1$ divided by $T$ (top), and the Knight shift (bottom). The arrows indicate $T_{cH}$ under elevated fields.

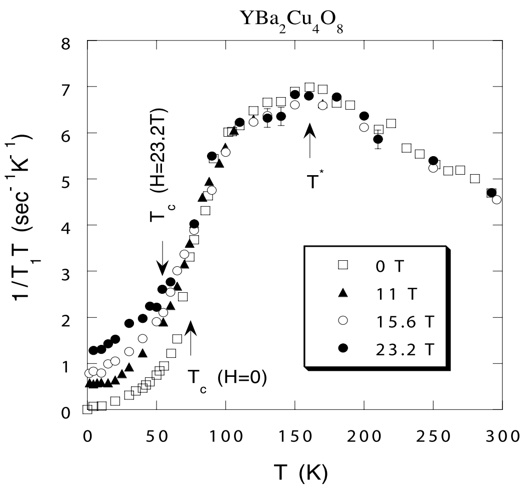


**Figure 2.** $1/T_1T$ of $^{63}$Cu under various field in the underdoped material $YBa_2Cu_4O_8$.

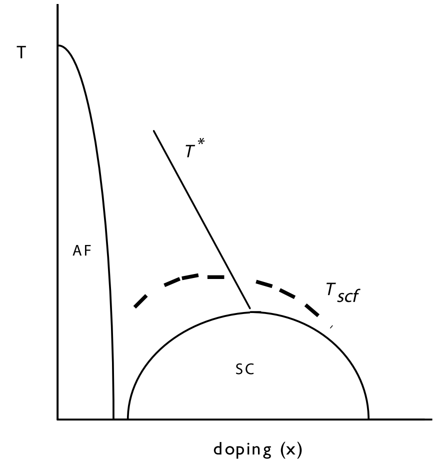


**Figure 3.** Phase diagram suggested from the present study. $T_{scf}$ and $T^*$ represent the superconducting fluctuations and the $H$-insensitive PG temperatures, respectively.